# OPERATION OF A FIVE-STAGE 40,000-CM$^2$-AREA INSULATOR STACK AT 158 KV/CM

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*Abstract*

We have demonstrated operation of a 3.35-m-diameter insulator stack at 158 kV/cm with no total-stack flashovers on five consecutive Z-accelerator shots. The stack consisted of five +45°-profile 5.715-cm-thick cross-linked-polystyrene (Rexolite-1422) insulator rings, and four anodized-aluminum grading rings shaped to reduce the field at cathode triple junctions. The width of the voltage pulse at 89% of peak was 32 ns. We compare this result to a new empirical flashover relation developed from previous small-insulator experiments conducted with flat unanodized electrodes. The relation predicts a 50% flashover probability for a Rexolite insulator during an applied voltage pulse when $E_{max}e^{-0.27/d}(t_{eff}C)^{1/10} = 224$, where $E_{max}$ is the peak mean electric field (kV/cm), d is the insulator thickness (cm), $t_{eff}$ is the effective pulse width (μs), and C is the insulator circumference (cm). We find the Z stack can be operated at a stress at least 19% higher than predicted. This result, together with previous experiments conducted by Vogtlin, suggest anodized electrodes with geometries that reduce the field at both anode and cathode triple junctions would improve the flashover strength of multi-stage insulator stacks.

## I. INTRODUCTION

Sandia National Laboratories is proposing to design and build a 40-MA z-pinch accelerator (ZX) for inertial-confinement-fusion, equation-of-state, plasma-physics, and high-energy-density-physics experiments. The machine would also serve as a testing facility for pulsed-power research required to develop higher current (~80 MA) drivers. The ZX design would build upon experiments performed on the Proto-II,[1] Saturn,[2] and Z[3-11] accelerators, which have delivered 5, 8, and 20 MA to z-pinch loads, respectively.

To optimize the ZX design, we are conducting a series of experiments to improve the understanding of the performance of large-area multi-stage insulator stacks. Results of the first series of experiments are reported in Sec. II. In Sec. III, we use small-insulator-flashover data[12-18] to develop a new empirical flashover relation. In Sec. IV, we compare the relation's predictions with Z-stack measurements, and previous results obtained by Vogtlin[19] with anodized electrodes and an anode plug.[20]

## II. Z-STACK EXPERIMENTAL RESULTS

The Z accelerator[3-11] has thirty-six modules which deliver power to four insulator-stack levels at the accelerator's water-vacuum interface. Nine modules deliver power to each of the four levels. The source impedance of nine modules in parallel is 0.48 ohms. For the stack-flashover experiments, only the modules connected to the uppermost level were operated. This level, shown in Fig. 1, consisted of five +45°-profile 5.715-cm-thick 3.35-m-outer-diameter cross-linked-polystyrene (Rexolite-1422) insulator rings,[21] and four 0.9525-cm-thick hard-anodized-aluminum grading rings.[6] The stack electrodes and grading rings were shaped to reduce the field at cathode triple junctions 15% below the value that would have been obtained with flat electrodes. All insulator and electrode surfaces were machined to a roughness with a root-mean-square value ≤81 μm.[6]

On five consecutive Z shots (#334-338), the total stack did not flash during the application of a 4.52-MV 93-ns-FWHM voltage pulse. The shots were taken at pressures between $6.1\times10^{-6}$ and $1.8\times10^{-5}$ torr. The stack had been subjected to a pulse with peak voltage ~3 MV on the previous 333 shots. After each of the 338 shots, the stack

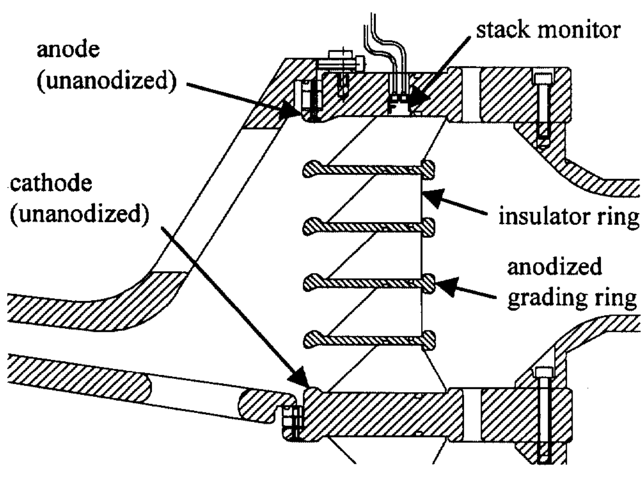


Figure 1. The uppermost stack level of the Z accelerator.

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14. ABSTRACT

**We have demonstrated operation of a 3.35m-diameter insulator stack at 158 kV/cm with no total-stack flashovers on five consecutive Z-accelerator shots. The stack consisted of five +45-profile 5.715-cm-thick crosslinked- polystyrene (Rexoiite-1422) insulator rings, and four anodized-aluminum grading rings shaped to reduce the field at cathode triple junctions. The width of the voltage pulse at 89% of peak was 32 ns. We compare this result to a new empirical flashover relation developed from previous small-insulator experiments conducted with flat unanodized electrodes. The relation predicts a 50% flashover probability for a Rexolite insulator during an applied voltage pulse when E,,e~0~27d(t&)o = 224, where E,,, is the peak mean electric field (kV/cm), d is the insulator thickness (cm), t,n is the effective pulse width (ps), and C is the insulator circumference (cm). We find the Z stack can be operated at a stress at least 19% higher than predicted. This result, together with previous experiments conducted by Vogtlin, suggest anodized electrodes with geometries that reduce the field at both anode and cathode triple junctions would improve the flashover strength of multi-stage insulator stacks.**

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was opened to atmospheric pressure, and the insulator rings were cleaned with Scotch-Brite™ (#96), ethyl alcohol, and TexWipes™ (TX 309). (The bottom ring was also regularly cleaned with 400-grit sandpaper.) None of the stack (or MITL) components were oiled for any of the shots.

Shots #334-338 were taken with no MITL electrodes or any other load hardware attached to the stack; hence the magnetic field at the plastic vacuum interface (~1 mT, due to displacement current) was orders of magnitude less than required for magnetic flashover inhibition. There were also no sources of charged particles or ultraviolet radiation, except for those inherent to the stack itself when operated at high voltage.

Six D-dot and three B-dot monitors were used to measure the stack voltage and current.[22] All monitors were located on a 1.651-m radius, as shown in Fig. 1. The D-dots were located at 20, 100, 140, 220, 260, and 340 degrees; the B-dots at 60, 180, and 300 degrees. The six D-dot and three B-dot signal averages for shot #338 are presented in Figure 2.

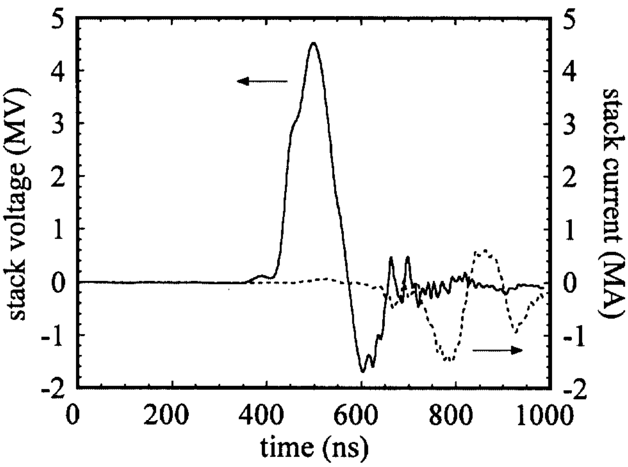


Figure 2. The stack voltage and current on Z-shot #338.

## III. THE NEW RCM RELATION

To facilitate comparison of these results with previous measurements, we develop a new insulator-flashover relation. We begin by considering a large population of +45°-profile insulators, each with thickness d and unit length, subject to a voltage pulse V(t) where V(t) = 0 for t < 0. We define $N_{unit}(0)$ as the size of the population and $N_{unit}(t)$ as the number of insulators that survive until time t without flashing. We make the simplifying assumption that the insulator failure rate is a function of the mean applied electric field $E(t) \equiv V(t)/d$, and that this function can be approximated as a power law:

$$\frac{1}{N_{unit}(t)}\frac{\partial N_{unit}(t)}{\partial t} = -\left(\frac{E(t)}{k}\right)^{\beta} \qquad (1)$$

where β and k are independent of t. Integrating Eq. 1 gives

$$s_{unit}(t) = \exp\left(-\frac{1}{k^{\beta}}\int_0^t E^{\beta}(\nu)\partial\nu\right) \qquad (2)$$

where $s_{unit}(t) \equiv N_{unit}(t)/N_{unit}(0)$ is the survival probability.

We now consider a large population of circular insulators, each with thickness d and circumference C (where C is greater than unit length), subject to the voltage pulse V(t). We define N(0) to be the size of the population, and N(t) the number that survive until time t. We model each insulator as C insulators in parallel, each with thickness d and unit length.[23] Assuming the initiatory flashover mechanism operates independently in each of a ring's unit-length components, the survival probability $s(t) \equiv N(t)/N(0)$ can be expressed as:

$$s(t) = s_{unit}^{C}(t). \qquad (3)$$

Combining Eq.'s 2 and 3 gives:

$$f(t) = 1 - \exp\left(-\frac{C}{k^{\beta}}\int_0^t E^{\beta}(\nu)\partial\nu\right) \qquad (4)$$

where $f(t) \equiv 1 - s(t)$. The failure probability f(t) equals 50% when

$$E_{max}\left(\frac{t_{eff}C}{\ln 2}\right)^{1/\beta} = k \qquad (5)$$

where

$$t_{eff} \equiv \frac{1}{E_{max}^{\beta}}\int_0^t E^{\beta}(\nu)\partial\nu \qquad (6)$$

is the effective pulse width.

We determine β and k empirically using the insulator-flashover results listed in Table 1. These were obtained with +45°-profile uncoated polymethyl methacrylate (PMMA) and cross-linked polystyrene (Rexolite) insulators operated at $\leq 10^{-4}$ torr, between flat parallel uncoated electrodes, with no external sources of charged particles or ultraviolet radiation, and a magnetic field due only to the displacement current that charges the capacitance defined by the insulator and its electrodes.[12-18] This set of conditions matches those of the Z experiments with two exceptions: the Z stack included coated (anodized) grading rings, and the Z electrodes were shaped to reduce the field at cathode triple junctions. (We later compare the Table 1 data with the Z results, and to those obtained by Vogtlin with anodized electrodes and an anode plug.)

We use four constant-insulator-thickness subsets of the data in Table 1 to determine β: the 0.5-, 1.0-, 1.27-, and 1.5-cm results, which have the largest range of pulse widths. The value of β that best fits each set is approximately 10. Setting β = 10, we observe that, for the data in the Table for which d ≥ 0.5 cm, k is approximately proportional to exp(0.27/d) where d is in cm. (This

Table 1. Summary of +45°-profile uncoated PMMA and Rexolite insulator-flashover measurements conducted at pressures $\leq 10^{-4}$ torr, with flat uncoated electrodes and no external sources of charged particles or ultraviolet radiation, and effectively no magnetic field.

| reference | material | $E_{max}$ (kV/cm) | d (cm) | $t_{eff}$ (μs) | C (cm) | $k_{RCM}$ | $t_{89\%}$ (μs) | A ($cm^2$) | $k_{JCM}$ |
|---|---|---|---|---|---|---|---|---|---|
| Anderson[15] | PMMA | 405 | 0.6 | 0.00979 | 20 | 228 | 0.0100 | 20 | 254 |
| Glock[12] | PMMA | 295 | 1.257 | 0.00493 | 19.99 | 195 | 0.00533 | 35.54 | 175 |
| Milton[14] | PMMA | 1100 | 0.254 | 0.000631 | 14.91 | 247 | 0.000778 | 5.36 | 395 |
| Milton[14] | PMMA | 651 | 0.508 | 0.000507 | 14.11 | 242 | 0.000495 | 10.14 | 231 |
| Milton[14] | PMMA | 523 | 0.762 | 0.000739 | 13.31 | 240 | 0.000920 | 14.35 | 213 |
| Milton[14] | PMMA | 444 | 1.016 | 0.00112 | 12.52 | 230 | 0.00152 | 17.98 | 201 |
| Milton[14] | PMMA | 417 | 1.27 | 0.00147 | 11.72 | 233 | 0.00178 | 21.05 | 197 |
| Milton[14] | Rexolite | 417 | 1.27 | 0.00147 | 11.72 | 233 | 0.00178 | 21.05 | 197 |
| Milton[14] | PMMA | 346 | 1.59 | 0.00736 | 10.71 | 235 | 0.00880 | 24.09 | 216 |
| Milton[13] | PMMA | 313 | 1.27 | 0.00627 | 11.72 | 202 | 0.00797 | 21.05 | 190 |
| Milton[13] | PMMA | 365 | 0.254 | 0.134 | 14.91 | 140 | 0.164 | 5.36 | 319 |
| Milton[13] | PMMA | 315 | 0.508 | 0.163 | 14.11 | 209 | 0.181 | 10.14 | 299 |
| Milton[13] | PMMA | 278 | 0.762 | 0.330 | 13.31 | 235 | 0.433 | 14.35 | 316 |
| Milton[13] | PMMA | 242 | 1.016 | 0.487 | 12.52 | 231 | 0.619 | 17.98 | 298 |
| Milton[13] | PMMA | 196 | 1.27 | 0.519 | 11.72 | 197 | 0.658 | 21.05 | 248 |
| Milton[13] | Rexolite | 223 | 1.27 | 0.723 | 11.72 | 232 | 0.902 | 21.05 | 297 |
| Vogtlin[16,18] | PMMA | 522 | 0.5 | 0.000836 | 10.37 | 196 | 0.00103 | 7.33 | 202 |
| Vogtlin[16,18] | PMMA | 471 | 0.75 | 0.000836 | 9.58 | 210 | 0.00103 | 10.16 | 189 |
| Yamamoto[17] | PMMA | 238 | 0.5 | 10.0 | 7.85 | 223 | 11.8 | 5.55 | 426 |
| Yamamoto[17] | PMMA | 179 | 1.0 | 10.0 | 9.42 | 223 | 11.8 | 13.33 | 350 |
| Yamamoto[17] | PMMA | 164 | 1.5 | 10.0 | 11.00 | 227 | 11.8 | 23.33 | 339 |

scaling must become invalid at sufficiently small values of d; it appears to fail at 0.254 cm when $t_{eff} \sim 0.1$ μs.)

Defining $k_{RCM} \equiv k e^{-0.27/d} = E_{max} e^{-0.27/d}(t_{eff}C/\ln 2)^{1/10}$, we include in the Table values of $k_{RCM}$. The average value for PMMA, excluding both 0.254-cm results, is 221; the standard deviation is 16 (7%). The average value for Rexolite is 232. Hence for $d \geq 0.5$ cm, $f(t) \approx 0.5$ when:

$$E_{max} e^{-0.27/d}\left(\frac{t_{eff}C}{\ln 2}\right)^{1/10} = \begin{cases} 221 \pm 16 & \text{(PMMA)} \\ 232 & \text{(Rexolite)} \end{cases} . \quad (7)$$

We refer to Eq. 8 as the restricted Charlie Martin (RCM) relation since strictly speaking, it applies only to the data in the Table with $d \geq 0.5$ cm. We note that, for the PMMA measurements, $t_{eff}$ ranges from 0.5 ns to 10 μs. Fig. 3 plots $E_{max}$ as a function of $e^{0.27/d}(t_{eff}C/\ln 2)^{-1/10}$.

To compare the data in Table 1 with the original JCM-scaling prediction[24] ($E_{max} t_{89\%}^{1/6} A^{1/10} = k_{JCM}$, where $t_{89\%}$ is the full width in μs of the applied voltage at 89% of peak, and A is the area in $cm^2$ of the vacuum-insulator interface), we include in the Table $t_{89\%}$, A, and $k_{JCM}$. For the PMMA results in the Table with $d \geq 0.5$ cm, the average value of $k_{JCM}$ is 256; the standard deviation is 71 (28%). Fig. 4 plots $E_{max}$ as a function of $t_{89\%}^{-1/6} A^{-1/10}$. It appears the data are more consistent with RCM scaling; however, we note the JCM relation was developed before most of the measurements in the Table were taken.

Assuming RCM scaling, Eq. 4 gives the cumulative failure probability for a single insulator ring (selected randomly from a large population.) Following ideas developed by Smith[25], we calculate the RCM probability that all of the rings in an n-stage insulator stack flash between times 0 and t is given by:

$$F(t) = \int_0^t \cdots \int_{t_{n-2}}^t \int_{t_{n-1}}^t n!\left(\prod_{i=1}^{n} \frac{\partial f_i}{\partial t_i}\right) \partial t_n \partial t_{n-1} \ldots \partial t_1 \quad (8)$$

where

$$f_i(t) \equiv 1 - \exp\left(-\frac{C}{k^\beta}\sum_{j=1}^{i}\left(\int_{t_{j-1}}^{t_j}\left(g_j E(\nu)\right)^\beta \partial\nu\right)\right) \quad (9)$$

and $t_0 \equiv 0$. Assuming that, if one or more rings flash, the voltage redistributes itself equally across the remaining unflashed rings, and neglecting azimuthal-transit-time effects,[25] $g_j = (n/n+1-j)$. Imperfect redistribution would increase, and transit-time effects decrease, the effective values of $g_j$.

## IV. APPLICATION OF RCM TO THE Z-STACK AND VOGTLIN RESULTS

Assuming Eq.'s 7-9 apply to the Z stack, we estimate that the total-stack-flashover probability is 81% for the conditions described in Sec. I. The measured value is ≤17%, which suggests $k_{RCM} \geq 276$, or ≥19% larger than the value given by Eq. 7 for Rexolite. We speculate the difference is due to the anodized grading rings in the Z stack, and Z's electrode geometry, which reduced the field at cathode triple junctions.

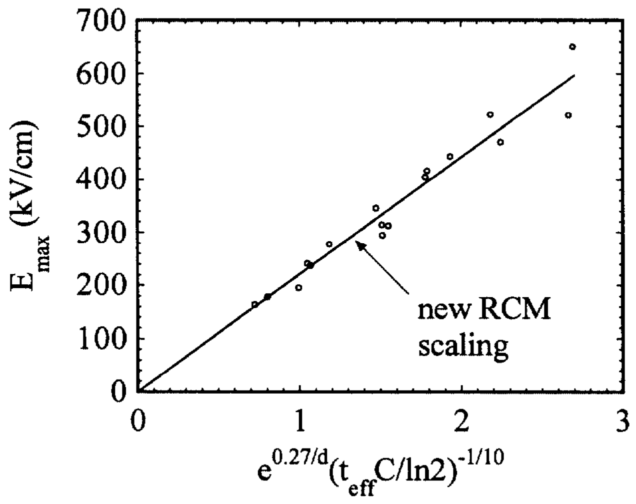


Figure 3. $E_{max}$ as a function of $e^{0.27/d}(t_{eff}C/\ln 2)^{-1/10}$ for the PMMA data in Table 1 with $d \geq 0.5$ cm. For these measurements, $t_{eff}$ ranges from 0.5 ns to 10 μs.

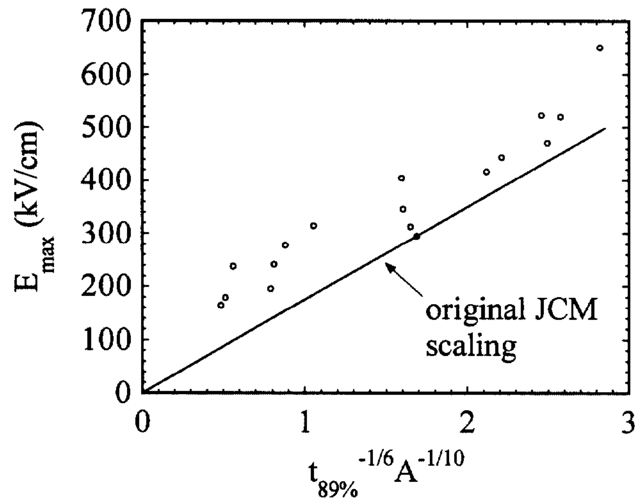


Figure 4. $E_{max}$ as a function of $t_{89\%}^{-1/6}A^{-1/10}$ for the PMMA data in Table 1 with $d \geq 0.5$ cm. The original JCM relation[24] ($k_{JCM}$ = 175) is also plotted.

Measurements by Vogtlin of the flashover-strength of an insulator with anodized electrodes and an anode plug[19] (which reduced the field at the anode triple junction[20]) also exceeded the value predicted by Eq. 7. Vogtlin observed that a 1-cm-thick +45° Lexan insulator with $t_{eff}$ = 67 ns and C = 8.80 cm did not flash when $E_{max}$ = 391 kV/cm, indicating $k_{RCM} \geq 294$ under these conditions. (We note the flashover strength of Lexan is less than that of PMMA and Rexolite when tested under identical conditions, for $t_{eff} \sim 0.6$ μs.[13])

The Z-stack and Vogtlin results suggest anodized electrodes with geometries that reduce the field at both triple junctions would improve the flashover strength of multi-stage insulator stacks. Additional experiments are needed to develop a new flashover relation more appropriate to these conditions.

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